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Superconducting SQUID Amplifiers for IR Detectors and Other Applications:

Phase II Final Report

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May 1, 1993

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I. Introduction

The subject of this report is a completed Phase II SBIR project to develop a superconducting analog multiplexer circuit. The intended application of the multiplexer is as a component of processing circuitry for a superconducting infrared focal plane array (IR FPA). Development of the IR FPA is in progress under a separate contract. Among the accomplishments that are described below is the fabrication and testing of a functioning, superconducting, 20-input multiplexer, appropriate for use with an IR FPA.

The motivation for developing a superconducting multiplexer circuit derives primarily from the significant potential advantages of an all-superconducting IR FPA system, i.e. a system in which the detectors, as well as the associated processing circuitry, are superconducting. Section III of this report reviews the subject of superconducting IR FPAs. Chief among the advantages of such systems is the potential for larger arrays with greater numbers of detectors than is now possible. New, larger arrays will generate data at rates beyond the capabilities of conventional semiconductor circuitry. Superconducting circuit elements like A to D converters, however, have a significantly larger bandwidth than their semiconducting counterparts, enabling them to achieve these data rates. In addition, the low power dissipation of superconducting devices means that the refrigeration power requirements for larger arrays will remain within acceptable limits. The optical bandwidth and radiation hardness are two other areas where the all-superconducting IR FPA is potentially superior to conventional semiconductor systems.

In large IR FPAs multiplexing is essential for reducing the number of wires between the array and the room-temperature display. If a system with, for example, $256 \times 256 = 65,536$ detectors were to have one wire for each detector, the result would be extremely difficult, if not impossible, to construct, and present a tremendous heat flux from room-temperature to the arrays. A multiplexing circuit is essential for circumventing these problems.

All tasks in the Statement of Work of the Phase II contract have been successfully completed. In one important respect, they have been exceeded, in that the contract required the fabrication of a five-input multiplexer, whereas a more ambitious circuit was in fact fabricated and tested, namely a 20-input multiplexer.

II. Brief summary of what was accomplished in this project

Two types of superconducting multiplexer circuits were investigated through design, fabrication and testing. These are shown in Figs. 1 and 2. After extensive testing of several variations, the first type was eliminated because it required uniformity of device characteristics at a level far exceeding present-day fabrication capabilities. The second circuit functioned as designed. Three-input and twenty-input versions were designed, fabricated in niobium-based Josephson junction technology and tested.

Among the performance characteristics that were evaluated for the second multiplexer circuit were crosstalk level, gain, noise, dynamic range and bandwidth. The crosstalk level was characterized as the fraction of the input signal on one detector that leaked into another detector. This was less than 1/150 with the limit set by the sensitivity of the instrumentation used for the measurement. A typical measured value for the small-signal gain from a selected input to the single output was 7.8x. The noise at the single output with all inputs in the "off" state was 1 nV/ $\sqrt{\text{Hz}}$. The calculated bandwidth of the 20-input multiplexer was 31 GHz. The dynamic range is of a system with a 10 KHz bandwidth is 54 dB.

III. Description of the technology of superconducting IR FPAs

The all-superconducting IR FPA is based on a monolithic chip that integrates the detector array and the processing electronics. The architecture of this chip consists of thin films patterned into circuits on a flat silicon substrate which is itself "micromachined", i.e. shaped by a special process that produces micron-sized structures in the silicon. The purpose of these structures is to increase detector sensitivity. The circuits become superconducting at low temperatures with some of them functioning as IR detectors, and others processing the outputs of the detectors by multiplexing, digitizing, or performing other functions. The characteristics of two technologies are therefore crucial to the final product, thin-film superconducting circuitry, and silicon micromachining.

Figure 3 shows one of the superconducting detectors¹. A superconducting thermal sensor is fabricated by first depositing a film of silicon nitride on top of a silicon substrate, next removing all silicon in a region underneath the silicon nitride film, and then patterning the suspended film into a square panel supported at its corners only by four thin-film legs. The panel and legs are 3000 Å thick, and the legs are typically 100 microns long by 10 microns wide. Infrared light falling on the panel and absorbed by it generates heat which can flow out to the substrate only through the legs which, because of their minute cross-sections ($\sim 5 \mu\text{m}^2$), have extremely small thermal conductances. The temperature of the island therefore rises considerably. A thin film Josephson junction, fabricated on top of the absorbing panel,

functions as a thermometer, measuring the temperature rise, which is proportional to the incident infrared light intensity. Because of the extremely low intrinsic noise of the Josephson junction, it is a very sensitive thermometer. The entire fabrication process, including micromachining, is performed by relatively common microelectronics techniques and is easily repeated thousands or hundreds of thousands of times over the entire surface of the substrate.

The current-voltage characteristics of the Josephson junction thermal sensors are shown in Fig 4. The steep part of the characteristic is the quasiparticle branch which is determined by the tunneling of single electrons through the junction. For operation as an IR detector the junction is voltage-biased on the quasiparticle branch. The midpoint voltage of the quasiparticle branch is called the gap sum voltage (i.e. the sum of the superconducting gaps of the junction base and counterelectrode) and it is this quantity that is temperature-dependent. As IR light causes the junction temperature to rise the gap voltage is reduced and the current out of the junction rises in proportion to the absorbed light. The reason for operating on the quasiparticle branch, and the reason for using a Josephson junction at all, is that the intrinsic noise is extremely low. Calculations estimate the magnitude at several picoAmps per $\sqrt{\text{Hz}}$ of bandwidth (10^{-12} A/ $\sqrt{\text{Hz}}$) and measurements have established that it is below a ceiling that is consistent with this value.

A fundamental aspect of the IR detection process described above is that its wavelength dependence is determined only by the absorption of light in the island on which the junction is fabricated. By a judicious choice of thin-film covering for the island, IR sensitivity can be obtained to hundreds of microns in optical wavelength.

An important requirement for the IR detection mechanism to work is that the temperature of the substrate is able to rise where IR light is absorbed. The entire chip is therefore mounted in a vacuum with the front face oriented towards an IR-transparent window and the back cooled through contact with a cold block. Temperatures below the superconducting transition temperature T_c of the Josephson junction must be maintained. In the last year Josephson junction IR detectors have been fabricated from niobium with a T_c of 9.2 K and niobium nitride with a T_c of 15 K.

One of the advantages of using a superconducting IR detector is that its impedance is well matched to that of other superconducting circuit components. These include superconducting amplifiers of the dc SQUID variety, and the multiplexer circuit which is described in this report.

IV. Multiplexer circuit I

Versions of multiplexer circuit I, with two and three inputs were tested. The schematic is shown in Fig. 1. The circuit has a bridge configuration, and the output is the voltage difference between points on the two different branches of the bridge. One branch is a series of dc SQUIDs, (the "signal" SQUIDs), in series with a biasing resistor; the other branch is a single dc SQUID, (the "null" SQUID), also in series with a biasing resistor. Each signal SQUID has two inputs, a signal input and a control input. The "low" side of all of the control inputs meet at a node which is connected to the single input of the null SQUID. Thus, current injected into the control line of any signal SQUID will also flow through the null SQUID input.

Figure 5 illustrates how the circuit functions. To select an input signal for reading, an ac current is injected into the control input of the corresponding signal SQUID. If the signal input has zero current, then equal (alternating) voltages will be generated in the signal and null SQUIDs, and the bridge output is zero. If, however, there is a signal current in the SQUID to which control current is applied, a phase shift is introduced between the voltages in the two branches of the circuit, and their difference is nonzero. The amplitude of the difference voltage is the multiplexer output, as it depends linearly on the input level, in the small signal limit. The difference voltage is then sent on to the input of subsequent processing circuits.

Figure 6 shows test results for a two-input version of the SQUID. The circuit works qualitatively as it should, giving a large alternating output when the signal input is high. When the signal input is zero however, and the output should be zero, there is still some residual output. One way to characterize quantitatively the seriousness of the residual output voltage is to measure the ratio of the smallest multiplexer output to the largest output; the smallest output being the residual voltage. The photos in Fig. 6 show the smallest and largest outputs from one circuit that was tested. The ratio is approximately 1/14, or 7 %.

A study was undertaken to determine the origin of the residual offset voltage in the type I multiplexer circuits. The cause was identified as nonuniformity of device characteristics, which produces differences in the voltages of the signal and null SQUID when there should be none. One type of nonuniformity is variations in the critical currents of the SQUIDs. A difference of 1 % between the critical currents of the signal and null SQUIDs will result in a 1 % difference in the amplitude of the voltage versus flux relations of these two SQUIDs². This produces a residual voltage of 0.5 % of the maximum possible multiplexer output signal (the maximum multiplexer output is twice the amplitude of the voltage versus flux relation of a single SQUID).

The design specification of the Hypres fabrication process critical current uniformity is $\pm 5\%$ or better in a chip of area $[0.5 \text{ cm}]^2$ (the multiplexer test circuits fit within this area). By the calculation given above, critical current variations at that level should produce a residual voltage of 5% of the maximum multiplexer output. This is not too far off the measured values of 7% . The residual offset is therefore primarily a consequence of nonuniformities of Josephson junction critical current, even when these are within specifications. The obvious question is whether the circuit as a whole can be useful, even in the presence of the residual voltage.

To obtain a dynamic range of more than $14\times$, it must be possible to multiplex signals in which the output voltage is less than the residual voltage. This would be relatively simple if the residual voltage functioned as an offset, since an offset can be subtracted from all measurements. However, the effect of nonuniformity in SQUID critical currents is to introduce a constant signal that is *out of phase* from the true signal, and therefore adds to the amplitude in *quadrature*. A simple offset subtraction will not work. Were it not for the residual signal, the lower limit of small signals would be the noise of the multiplexer itself, or the inputs to the multiplexer. An estimate of the resulting dynamic range, in the case that the multiplexer noise dominates, is $3000\times$, or 70 dB in a 10 kHz bandwidth.

The conclusion is, therefore, that critical current nonuniformities that are within the present design specifications of the fabrication process limit the dynamic range to approximately $14\times$. To achieve a dynamic range of $1000\times$ would require a $100\times$ improvement in the critical current uniformity of the fabrication process, which is unlikely in the near future.

V. Multiplexer circuit II

The second type of multiplexer circuit tested is shown in Fig. 2, along with a load-line model showing the operating bias points when a detector is selected. The detector junctions serve as both the thermometers as well as the multiplexing switches, which affords a very simple and compact implementation of a multiplexed detector array system. All detectors are connected in series with each other and with the pickup coil of a SQUID amplifier. A bias resistor, connected across the series array in parallel, provides the bias. The value of the bias resistor is less than or equal to the dynamic resistance, r_d of the detector junction at the gap sum voltage, so the junction is effectively voltage-biased. All detector junctions have magnetic control lines over them which allows suppression of the critical current of the selected junction. The SQUID amplifier is used to measure the current flow through the detector in response to changes in the quasiparticle current-voltage characteristic caused by temperature changes in the detector.

A read cycle of a selected detector proceeds as follows. First, the multiplexer bias is reduced to zero so that all detector junctions are reset. The detector which is desired to be read out is selected by applying dc current to the magnetic select line which suppresses the Josephson current of this junction to near zero. After the junction has been selected, the multiplexer bias current is increased to a value which biases the detector on its quasiparticle branch. On this part of the current-voltage relation, the current which flows through the detector is most sensitive to temperature-induced changes in the gap sum voltage. It is also essential that all non-selected detectors remain in the zero voltage state, in order that they remain insensitive to temperature. For this reason, the maximum current allowable in the selected detector is equal to the critical current of the nonselected detectors (all detectors are assumed to have the same critical current), since when this current is exceeded a second detector junction will be switched into its finite-voltage, temperature-sensitive, state. In principle this circuit provides unlimited rejection of nonselected inputs since the non-selected detectors are biased on their Josephson branches where voltage is always zero.

Figure 4 shows the current through the selected detector junction, with and without illumination. This current is measured by the SQUID whose input coil is in series with the junction. The bias voltage is selected on the quasiparticle branch of the IV curve, but at somewhat lower bias current than the midpoint of that branch.

Noise, whether thermal or due to external sources will reduce the current range over which the multiplexer will function, by momentarily reducing the critical currents of non-selected detectors. The reduction in range can be estimated by using a simple thermal activation model for the switching of the junction out of the superconducting state³. If the lifetime of the superconducting state is τ_1 with the bias current $I < I_c$, the lifetime may be expressed as:

$$\tau_1 = (\omega_a/2\pi)\exp(-u_0/k_b T) \quad (1)$$

here ω_a is the attempt frequency for tunneling out of the superconducting state, u_0 is the potential barrier to tunneling, k_b is Boltzmann's constant, and the ambient temperature is T . We may set ω_a equal to the junction's plasma frequency for most cases of interest so $\omega_a = \sqrt{(eI_c/\hbar C)}$, where the junction capacitance is C , and also the coupling energy is $e_c = \hbar I_c/2e$. Also, u_0 is a function of the bias current,

$$u_0 = e_c[2(1-I/I_c)]^{3/2} \quad (2)$$

From these equations we find that a detector with a critical current of $220 \mu A$, biased at $210 \mu A$ (95 % of the critical current) will have an expected zero-voltage-state lifetime of $\tau_1 \approx 3 \times 10^4$ sec, more than sufficient for a multiplexing circuit with a required cycle time (to read all detectors) of 1 ms or less. At higher temperatures, the bias range is reduced, although for operation at $T = 10$ K, 90 % of the critical current range (for a $220 \mu A$

detector critical current) is available with ample noise immunity. From this discussion it is clear that a practical multiplexer can expect to handle an input current range of better than 75% of I_c .

VI. Evaluation of multiplexer circuit II performance

a. Description and measurement methods

The performance of the circuit can be characterized by the following specifications:

(i) crosstalk (ii) overall gain of the circuit (iii) noise added by the circuit (iv) dynamic range (v) bandwidth. The multiplexer circuit was built to include input signals which simulate those from superconducting infrared detectors. The input signals were provided by Josephson junctions which differ from "real" superconducting infrared detectors in that they were not fabricated on back-etched areas of the substrate (see Fig. 3), but rather on solid areas of the same silicon substrate as the multiplexer circuit. To simulate infrared light shining on the detectors, power was dissipated by joule-heating of annular thin film resistors located around each Josephson junction.

In Fig. 7 we show the measured gap suppression of a typical detector junction as a function of power dissipated in the heater resistor (the heater resistance is $2\ \Omega$). The junction is $8 \times 8\ \mu\text{m}^2$ in area, with a critical current $I_c = 220\ \mu\text{A}$ ($J_c = 340\ \text{A}/\text{cm}^2$) and normal state resistance of $10.5\ \Omega$. The detector is immersed in liquid helium and in direct contact with the silicon substrate, so the amount of power required to suppress the gap voltage is relatively large, about $300\ \mu\text{W}$.

In addition to suppressing the gap voltage, an increase in the detector temperature also reduces the critical current. This is shown in Fig. 8, which is a graph of junction critical current as a function of heater power. I_c is suppressed by a factor of two at a heater power of $128\ \mu\text{W}$. In a real system the dynamic range of the multiplexer is limited by the reduction of critical current attendant upon warming of the junction. This occurs when infrared light warms up one of the *nonselected* detectors so much that its critical current is reduced below the bias current, and it switches into the infrared-sensitive state.

We have measured the magnitude of this limitation to the dynamic range by slowly increasing the power dissipated in a resistor surrounding a selected detector. When the current level in the *selected* detector equals the critical current of a *nonselected* detector, the upper limit of the dynamic range has been reached. The current level in the selected detector was found to increase by $5.2\ \mu\text{A}$ for a $1\ \mu\text{W}$ increase in resistor power (at a base heater power of $18\ \mu\text{W}$). The decrease in critical current of the nonselected detector is shown in Fig. 8. The two current levels are equal at $175\ \mu\text{A}$ of detector current which is

approximately 75% of the detector critical currents (i.e. up to $0.75 I_c$ where $I_c = 220 \mu A$). This is an upper limit to the dynamic range. A complete discussion of dynamic range is given in Section VI.e below.

In the development of the circuit, two designs were implemented, a 3-input multiplexer and a 20-input device. Correct operation of the 3-input multiplexer is demonstrated by the photographs shown in Fig. 9. The input signal is a sinusoidal drive to the heating elements of $500 \mu A$ which is equivalent to a maximum heating power of $0.5 \mu W$. This signal is applied first to input #1 and then to #2. The photos show the multiplexer output with either #1 or #2 inputs selected. The amplifier SQUID bias is adjusted to a region of large $dV/d\phi$, i.e. where it is most sensitive. As can be seen from the photographs the circuit performs as expected, giving an output only when the channel with a non-zero input signal is selected. In addition, there is no residual output from the selected detector when its input is at zero, unlike multiplexer circuit I (compare Fig. 6).

b. Crosstalk

The crosstalk in the 20-input multiplexer was quantified in two ways. In both tests, the crosstalk was measured between channel #10 and the other channels; but the two tests measured crosstalk in opposite directions, i.e. *from* channel #10 in one test, and *to* channel #10 in the other test.

The procedure for the first test was to put an ac input signal on channel #10 only, and select each of the other channels successively for reading, while measuring the multiplexer output with a lock-in amplifier. The lock-in amplifier, besides being sensitive, has the added advantage that it can separate out spurious effects due to direct coupling between the heater leads and the SQUID. These spurious effects occur at $1/2$ the fundamental frequency of the signal on channel #10, and will be absent in a real IR FPA where input signals come from infrared light rather than joule-heating of resistors.

The SQUID was biased at an operating point about which the small signal response was linear. The results of these measurements are summarized in Table I. The data for this table were taken with a signal on input #10 only. Rejection ratios were then measured, i.e. the ratio of the multiplexer output when channel # 10 was selected, to the multiplexer output when another output was selected. As can be seen from the table, the average rejection is better than 150:1 for most inputs, and in fact this is a lower bound which is determined by the signal to noise ratio of our lock-in measurement (in the linear region the SQUID output signal was only $10 \mu V$ peak to peak). Needless to say, the 20-input multiplexer was fully functional.

In the second test, input #10 was selected, signal was applied to the remaining inputs in sequence and the multiplexer output was measured. The results of this test were nearly identical with those of the first test.

c. Gain of the circuit

The overall gain of the circuit was calculated in the small input signal regime, for the amplifier SQUID biased in the linear region where $dV/d\phi = 100 \mu V/\phi_0$. For this SQUID bias, a gain of 7.8x was measured, i.e. There was 7.8 μV of SQUID output for 1 μV of detector junction gap change.

d. Noise added by the circuit

The first step taken in measuring noise in the multiplexer, and locating the source, was to measure noise in the SQUID with all detectors in the zero- voltage state. This procedure showed the noise referred to the SQUID loop to be $4 \times 10^{-6} \phi_0/\sqrt{\text{Hz}}$, a very respectable value. Then one detector was biased and the noise was measured again. The noise increased to $5 \times 10^{-4} \phi_0/\sqrt{\text{Hz}}$. This corresponds to 3 nA/ $\sqrt{\text{Hz}}$ at a selected input of the multiplexer. The source of this noise may be current noise in the Josephson junctions themselves, or flux noise in the SQUID from current in the junctions or elsewhere.

e. Dynamic range

The dynamic range of the multiplexer circuit is the ratio of the largest signal to the smallest signal that the circuit can accommodate. As described in Section VI.a, the largest input signal that is possible without a second input switching on is 75 % of the critical current of a detector junction. For the circuits that were actually tested, this is 175 μA . The smallest signal is the noise in the multiplexer circuit, referred to the multiplexer input. For the twenty-input multiplexer that was tested, this is 3 nA/ $\sqrt{\text{Hz}}$. The dynamic range is then $175 \mu A / (3 \text{ nA} / \sqrt{\text{Hz}} \times \sqrt{\text{bandwidth}}) = 5 \times 10^4$ or 94 dB in a 1 Hz bandwidth. Assuming the final system operates with a 10 KHz bandwidth, the dynamic range of the multiplexer is 54 dB.

f. Bandwidth

The bandwidth of the multiplexer is determined by the L/R time constant of the loop formed by the SQUID input (which is the "L") and the detectors, and biasing resistor (which together constitute the "R".) The time constant is then $L/R = 2 \mu \text{sec}$, which corresponds to a bandwidth of $2\pi R/L = 300 \text{ MHz}$. Given that the ultimate time constant of the

infrared detectors themselves is estimated to be 1 msec, and that it is desired to multiplex all inputs within that time, the maximum number of inputs that can be multiplexed and meet these criteria is $1 \text{ msec} / 2 \text{ } \mu\text{sec} = 500$.

g. Remaining issues

The most important issue that remains to be addressed is the need for an integration circuit. This is because all multiplexing schemes must be accompanied by an integration circuit for each detector, if the signal-to-noise ratio is not to be degraded. In superconducting thin-film technology, the most direct way to accomplish integration is probably by means of an inductance-resistance series circuit. The cut-off frequency f_{co} is then given by $f_{co} = 2\pi R/L$; for which reasonable values may be achieved since very low values of R can be attained with superconducting circuits.

VII. Conclusion

Three-input and twenty-input multiplexers have been designed, fabricated and tested in niobium Josephson junction circuit technology. These multiplexers feature extremely low levels of crosstalk because non-selected inputs are kept in a superconducting, zero-voltage state. Measurements made for this project show that the crosstalk is less than 1% for any two detectors in a twenty-input multiplexer. Also, the multiplexer circuits that were tested had gains of 7.8x between any selected input and the one output. The type of multiplexer circuit developed here may be adapted for more inputs. For an IR FPA system with a 1 msec refresh rate, this circuit will be able to multiplex up to 500 detectors per refresh cycle. To preserve the signal-to-noise of individual infrared detectors at the multiplexer inputs, it will be necessary to use the multiplexer in conjunction with an integration circuit. The development of a superconducting integrator circuit is therefore the next link that should be developed in the chain of a complete superconducting IR FPA.

References

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- ² Principles of Superconductive Devices and Circuits, T. Van Duzer and C.W. Turner, Elsevier, New York, 1971, pg. 217.
- ³ T.A. Fulton and L.N. Dunkleberger, Phys. Rev. B 7, 4760, 1974.

Tables

Input selected	Multiplexer output (mv-rms)	Rejection ratio
1	0.00	≥ 300
2	0.00	≥ 300
3	0.00	≥ 300
4	0.04	75
5	0.00	≥ 300
6	0.02	150
7	0.00	≥ 300
8	0.03	100
9	0.02	150
10	2.99	NA
11	0.02	150
12	0.00	≥ 300
13	0.01	300
14	0.01	300
15	0.02	150
16	0.02	150
17	0.02	150
18	0.02	150
19	0.00	≥ 300
20	0.01	300

Table I. Results of crosstalk test on 20-input multiplexer. An ac signal at 1 KHz was put into input #10, and the output of the multiplexer was measured with a lock-in amplifier as each of the 20 inputs was selected. The uncertainty in all the measurements was ± 0.01 mV-rms. Rejection ratio of a given input is ratio of output when input #10 is selected to output when another input is selected.

Figures

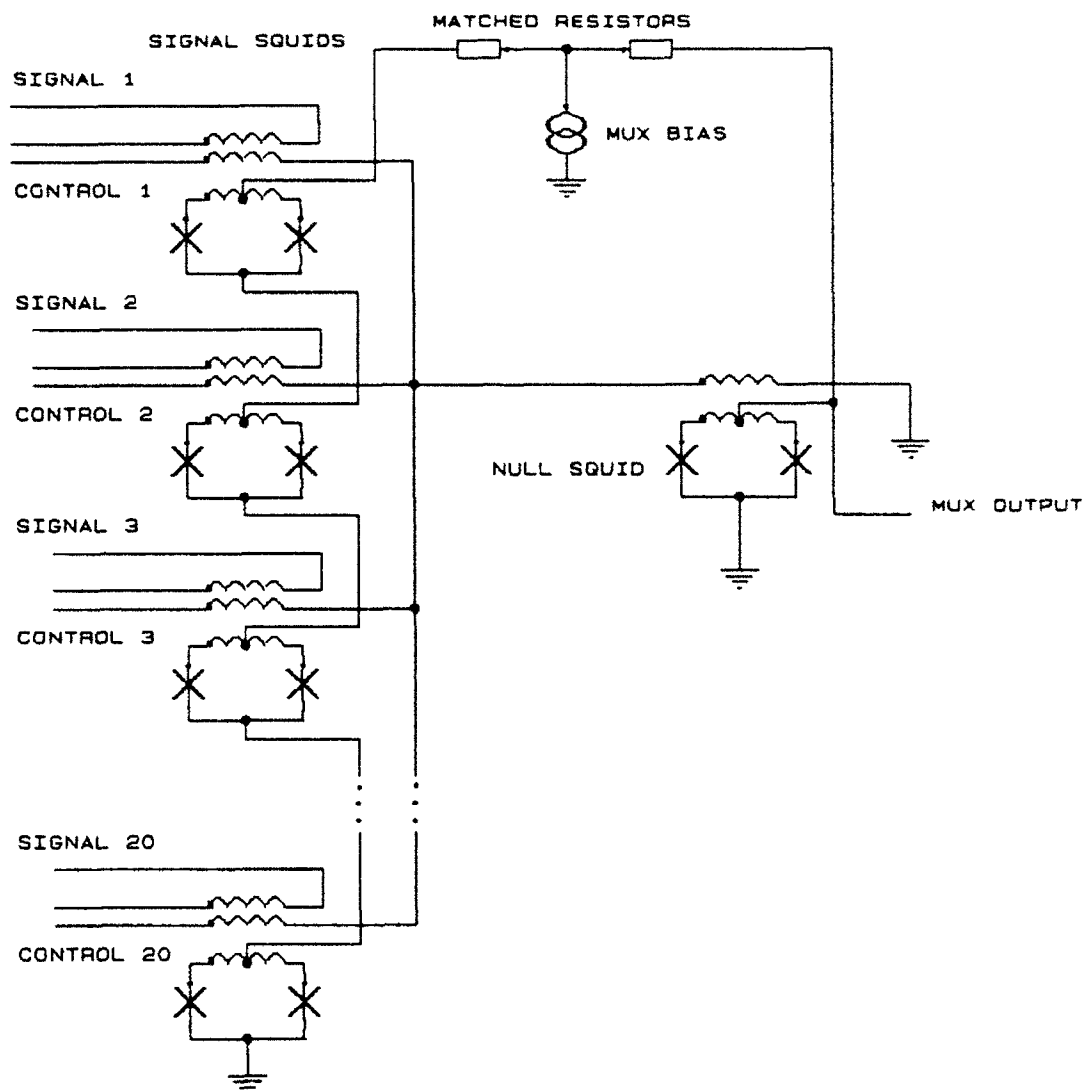


Figure 1 Multiplexer circuit I.

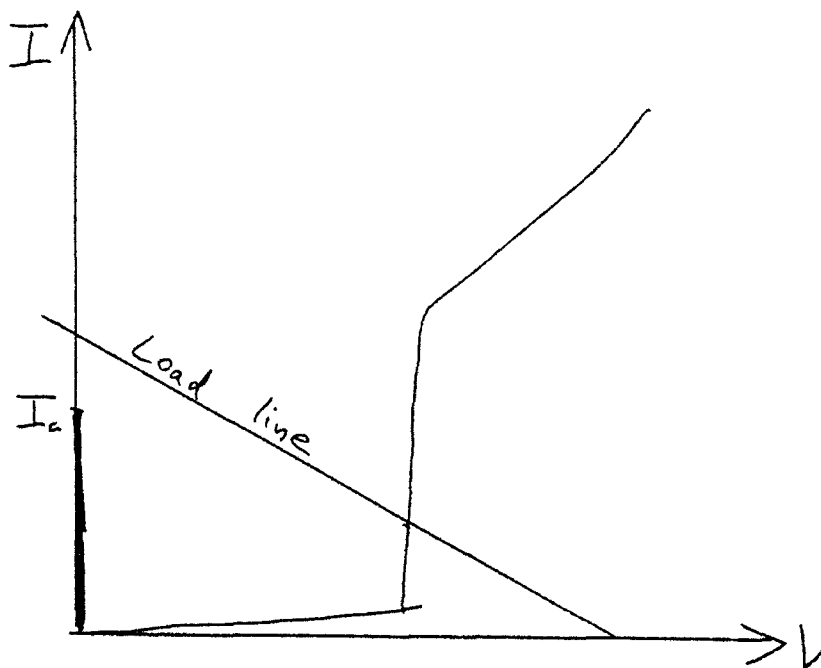
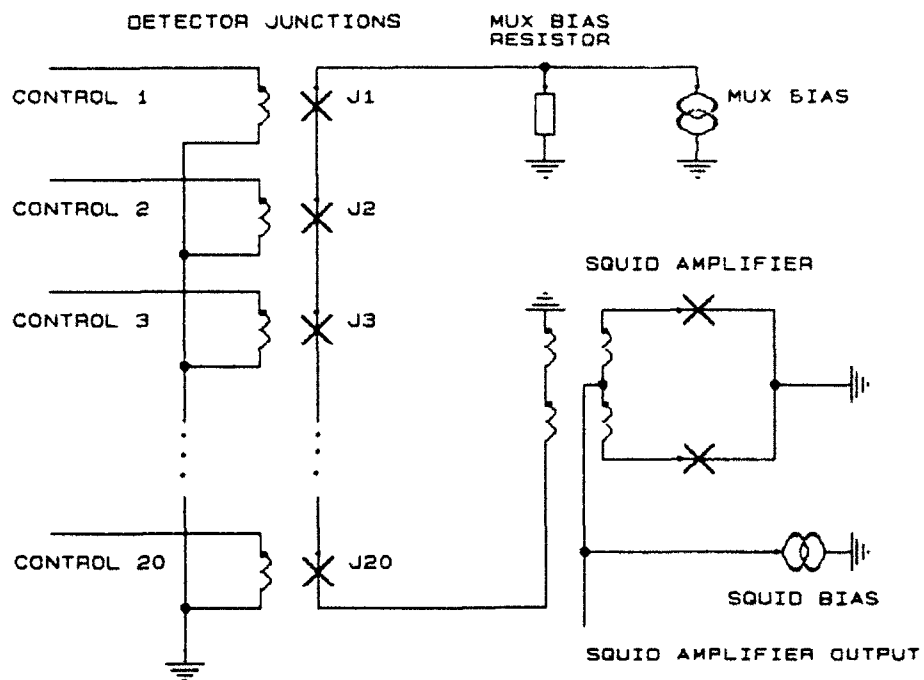


Figure 2 Multiplexer circuit II and load curve.

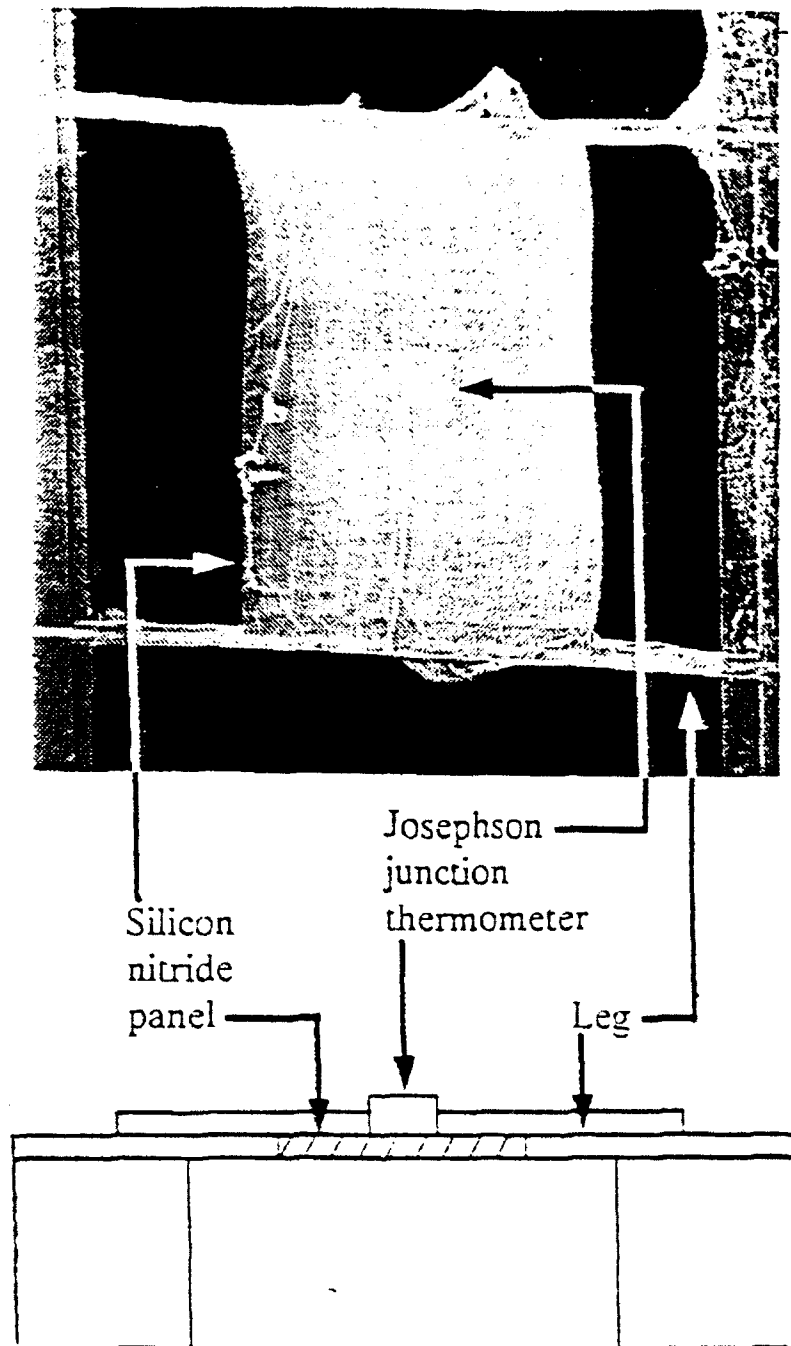


Figure 3 A superconducting infrared detector.

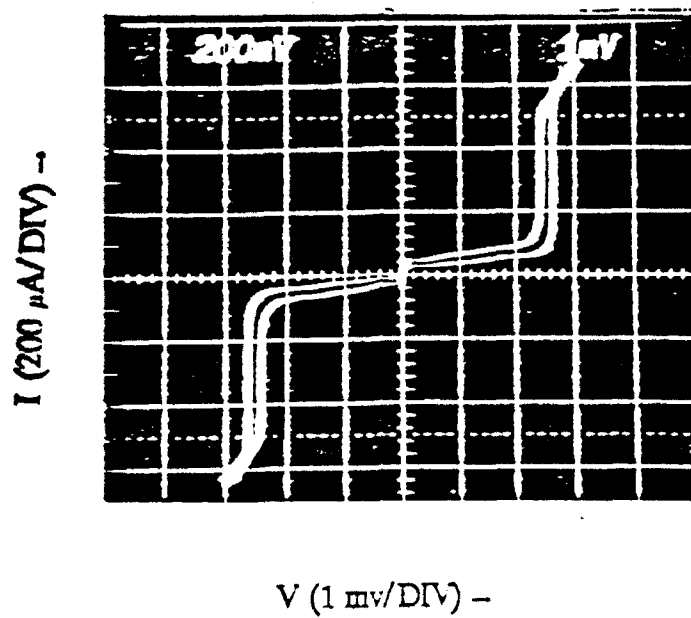


Figure 4 Current-voltage characteristics of superconducting infrared detector in presence and absence of light.

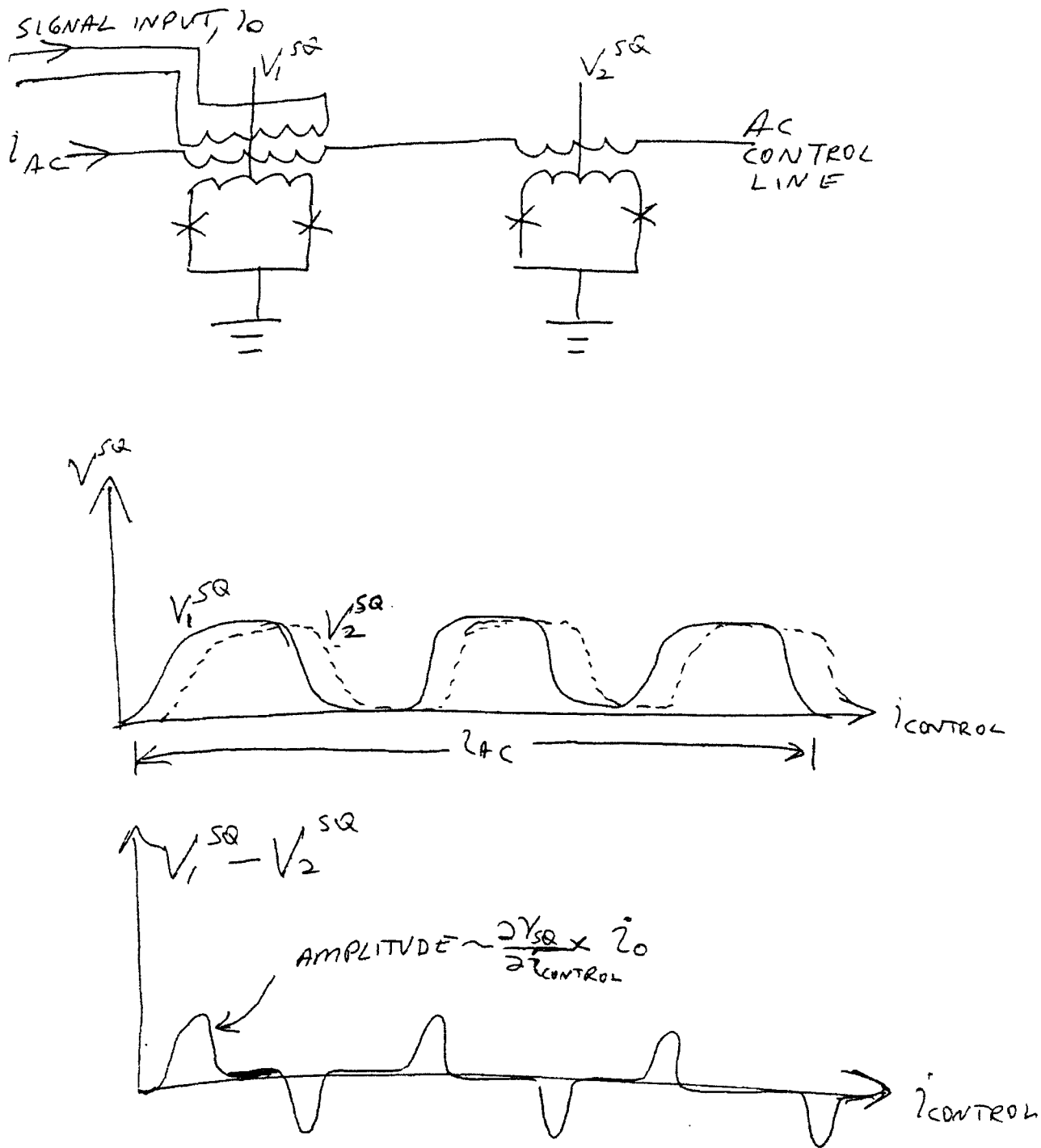


Figure 5 Operation of multiplexer circuit I. Top: detail of circuit showing one signal input and the corresponding control line. Middle: Voltage from two SQUIDs, V_1 and V_2 in the presence of a dc current in the signal input line, and ac signal in the control line. Bottom: Difference voltage of two SQUIDs, which is multiplexer output.

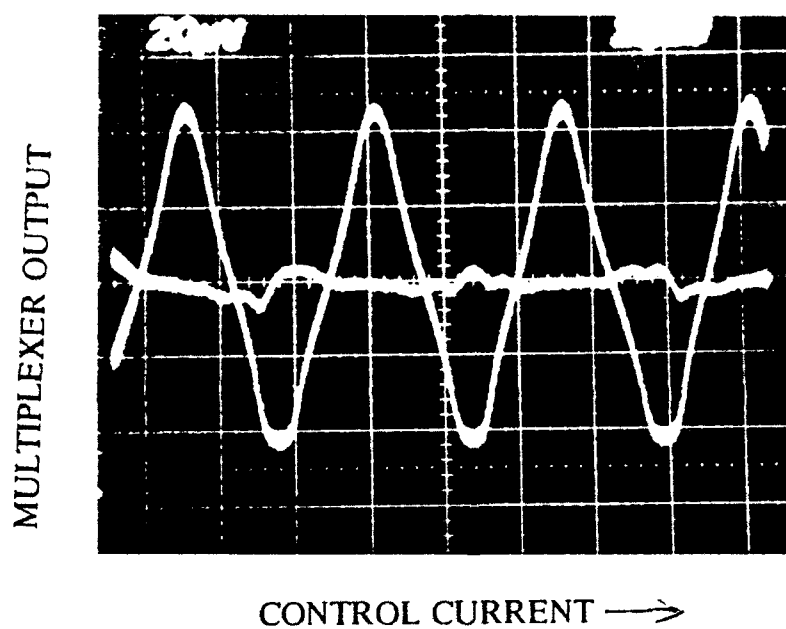


Figure 6 Test results for multiplexer circuit I, 2-input type.

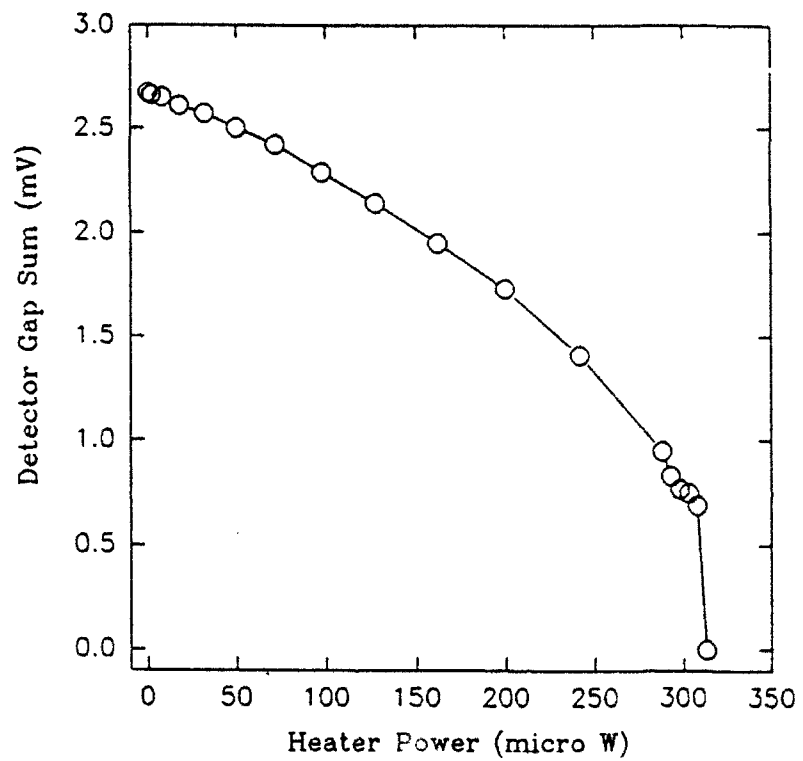


Figure 7 Voltage gap of niobium Josephson junction versus power dissipated in annular thin-film resistor.

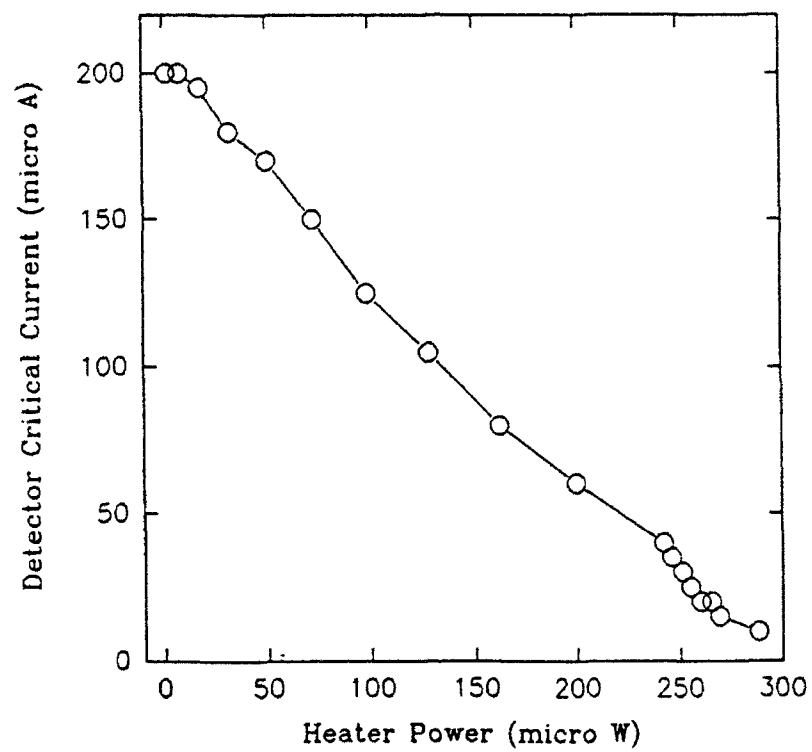


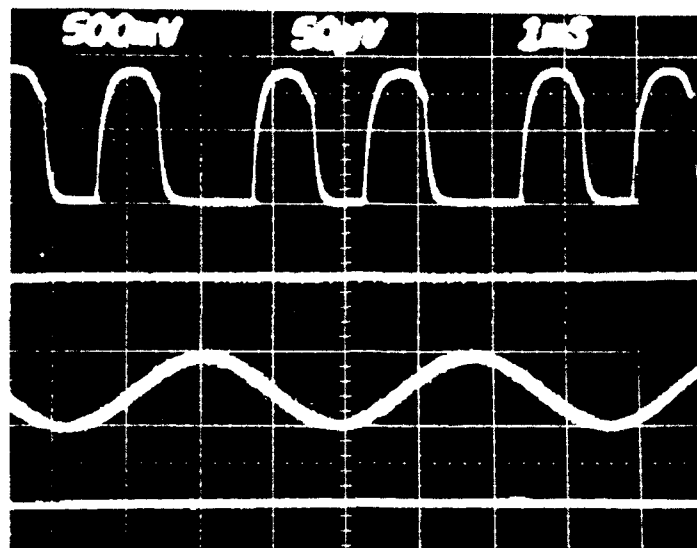
Figure 8 Critical current of niobium Josephson junction versus power dissipated in annular thin-film resistor.

Multiplexer output,
input #1 selected

Multiplexer output,
input #2 selected

Input #1

Input #2



Multiplexer output,
input #1 selected

Multiplexer output,
input #2 selected

Input #1

Input #2

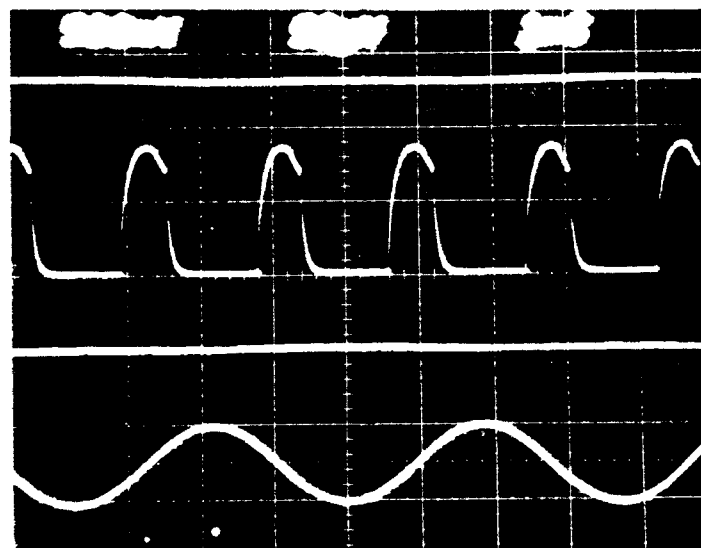


Figure 9 Tests of the 3 input multiplexer (multiplexer circuit II). In both photos, lower two traces are signal applied at inputs #1 and #2, and upper traces show output when input #1 and #2 is selected for reading.